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THE COMET RENDEZVOUS ASTEROID FLYBY MISSION: A STATUS REPORT

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The Comet Rendezvous Asteroid Flyby (CRAF) mission was approved for a New Start by the United States Congress in 1989. CRAF will be developed in parallel with the Cassini (Saturn orbiter/ Titan probe) mission. The two missions have been combined into a joint program because of the substantial cost savings (~$500M, or > 25%) which can be realized by using a common spacecraft design, several identical science instruments, a single management team, and a joint ground operations and data handling system for the two missions. CRAF and Cassini will be the first users of the new Mariner Mark II spacecraft which has been designed to carry out the next generation of planetary missions to the outer planets and to small bodies.

CRAF is a joint mission between the United States, Germany, and Italy. Each partner will provide both engineering hardware and science experiments. Cassini is a joint mission between the United States, Germany, Italy, and the European Space Agency (ESA), with ESA providing the Titan atmospheric entry probe, called Huygens.

Mission Profile. The ultra-fast Halley flyby missions in 1986 gave us a first, quick glimpse of a comet nucleus and the first *in situ* measurements of cometary gas and dust. Plasma measurements were carried out on both the 1985 ICE flyby of comet Giacobini-Zinner and the Halley flybys. These missions confirmed many of our basic ideas about comets and raised many interesting questions for further research. It was learned, for example, that comets contain a large amount of organic material, but the molecular composition of this material could not be uniquely determined. The nucleus of comet Halley was found to be dark and irregularly shaped, but very little was learned about the physical state and structure of the ices and grains within the nucleus.

The most important difference between CRAF and the earlier comet flyby missions is that CRAF will be a rendezvous mission, which means that the spacecraft will be maneuvered to follow an orbit around the Sun that precisely matches the comet's orbit. With a rendezvous, it will be possible to orbit the nucleus at an altitude of 10 - 100 km, to observe the comet over several years as its activity grows and wanes, to accurately measure the nucleus' mass and density, to move from place to place in the coma and tail of the active comet, to collect and study relatively undamaged cometary material, and to carry out a program of adaptive exploration using early results to plan later measurements.

CRAF's target is the short-period comet Kopff, which has been observed on 13 perihelion passages since its discovery in 1906 and is one of the most active of the comets that can be reached with a rendezvous mission. An active comet is highly preferred over one that has largely exhausted its supply of volatiles. Kopff has a perihelion distance of 1.58 AU.

The CRAF trajectory to Kopff is shown in Figure 1. Following launch on a Titan 4/Centaur expendable vehicle in April 1997, the spacecraft will perform a gravity assist flyby of Mars and two gravity assists at the Earth to fling it out toward the orbit of Jupiter. Between the two Earth flybys, the spacecraft will fly by the asteroids 88 Thisbe in June 2001, and 19 Fortuna in October 2002. A third asteroid flyby may also be possible en route to Kopff, following the second Earth flyby. In January 2006, the CRAF spacecraft will rendezvous with comet Kopff at a heliocentric distance of 5.3 AU, when the comet will be near its aphelion and in a state of low activity.

Comet Observations. The investigations tentatively selected for CRAF are listed in Table 1. A guest investigator program is planned to increase participation in the mission after launch.

The first order of business after arrival at comet Kopff will be to determine the mass of the nucleus by careful radio tracking during a series of increasingly close, slow flybys. Once the mass is known, the spacecraft will be maneuvered into orbit about the nucleus. If the comet nucleus has an average radius of 4 km and an average density of 0.8 g/cm^3, a nominal orbit would have a radius of 79 km and a period of 14 days. The semimajor axis, eccentricity, and inclination of the spacecraft's orbit can be easily changed with very little expenditure of fuel.

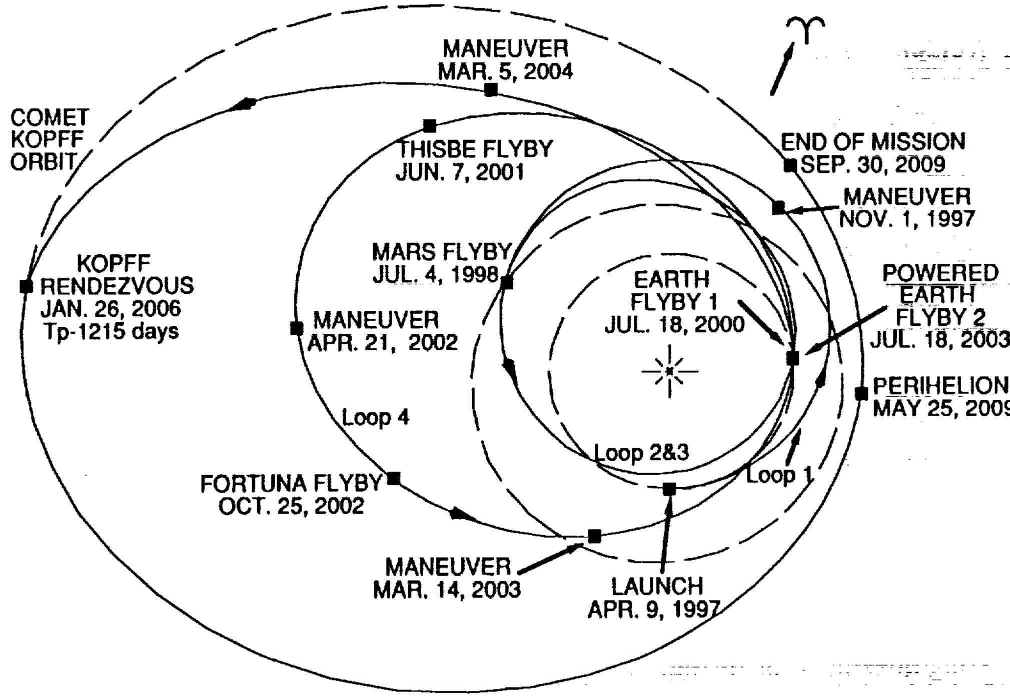

Figure 1. The interplanetary trajectory of the CRAF spacecraft, projected onto the ecliptic plane.

The initial flybys and orbits will also be devoted to mapping the nucleus and studying it to understand its physical properties. CRAF will carry two wide angle cameras and a narrow angle camera, each with 1024x1024 CCD detectors and an array of different filters. From a 79-km orbit, the spatial resolution of the narrow angle camera will be 0.95 meters/line-pair; as compared to the ~80 meters/line-pair resolution of the final picture of the nucleus of comet Halley by Giotto.

The visual/infrared mapping spectrometer (VIMS) will image the nucleus at visual and near-IR wavelengths in each of 352 spectral channels between 0.35 and 5.1 μm, with an angular resolution of 0.5 mrad/pixel (surface resolution of 40 m from a 79 km orbit). VIMS uses cooled CCD and InSb detectors. Surface materials that can be identified by VIMS include: silicates, ices, organics, oxides, salts, metals, emitting ions, and water in clays. When the comet is active, VIMS can also be used to map the distribution of many of the important molecules in the coma.

The third remote sensing instrument is the thermal infrared radiometer (TIREX) which will map the nucleus surface temperature distribution to determine thermo-physical properties and energy balance as well as to aid in the identification of surface materials. TIREX has one visual channel and 18 infrared channels between 5 and >50 μm. Its field of view is 1.5 mrad (118 m from a 79 km orbit). TIREX will be helpful in identifying regions where ices may be close to the surface of the nucleus and thus be possible sites of future activity.

Continued radio tracking of the spacecraft, including some data from very low orbits (<5 nucleus radii, or ~20 km), will yield measurement of the comet's mass to an accuracy better than 0.1%, as well as information about the mass distribution within the nucleus. The resulting value of bulk density will shed light on how the comet nucleus may have been accreted in the primordial solar nebula and what processing it might have undergone since its formation.

As it approaches the Sun, the comet will become more active and the spacecraft will move in and out through the cometary coma, measuring the properties of the gas and plasma and collecting dust for onboard analysis. The Cometary Matter Analyzer experiment will use secondary ion mass spectroscopy (SIMS) for analysis of collected samples of dust and gas. The very high mass resolution (>3000) of this instrument will allow the identification of different molecules with the

Table 1. CRAF Science Payload, Principal Investigators/Team Leaders, and Home Institutions

ISS	Imaging Science (facility)	Joseph Veverka	Cornell University
VIMS	Visual and Infrared Mapping Spectrometer (facility)	Thomas B. McCord	University of Hawaii
TIREX	Thermal Infrared Experiment	Francisco Valero	NASA Ames Research Center
CoMA	Cometary Matter Analyzer	Jochen Kissel	Max-Planck-Institut, Heidelberg
CIDEX	Cometary Ice and Dust Experiment	Glenn C. Carle	NASA Ames Research Center
CODEM	Comet Dust Environment Monitor	W. Merle Alexander	Baylor University
NGIMS	Neutral Gas and Ion Mass Spectrometer	Hasso B. Niemann	NASA Goddard Space Flight Center
CRIMS	Cometary Retarding Ion Mass Spectrometer	Thomas E. Moore	NASA Marshall Space Flight Center
SPICE	Suprathermal Plasma Investigation of Cometary Environments	James L. Burch	Southwest Research Institute
MAG	Magnetometer	Bruce T. Tsurutani	Jet Propulsion Laboratory
CREWE	Coordinated Radio, Electron, and Wave Experiment	Jack D. Scudder	NASA Goddard Space Flight Center
RSS	Radio Science (facility)	Donald K. Yeomans	Jet Propulsion Laboratory

same molecular weight (e.g., CH versus ^{13}C, or CO versus N_2). The CIDEX experiment will analyze bulk samples of collected dust and ice by alternating x-ray fluorescence measurements with pyrolysis and gas chromatography of the evolved gases.

A dust environment monitor, CODEM, will continuously measure the flux of particles as a function of particle momentum. If a grain is sufficiently electrically charged, it will also be possible to measure its vector velocity, and hence, its mass. The count rates from the momentum sensor will be made available to the spacecraft and to other science instruments in real time to allow them to close protective shutters or take other actions based on the dust flux.

CRAF will also carry a mass spectrometer, NGIMS, for the analysis of coma gases. Its electric quadrupole analyzer can analyze species from any of four sources: 1) an open or fly-through source for the analysis of highly reactive species, 2) a closed source which allows concentration of non-reactive species, 3) a thermal ion source, and 4) a SIMS source for concentrating heavy organic species.

There are two instruments for the study of the mass spectra and velocity distributions of ions. CRIMS can measure thermal ions with temperatures as low as 25 K while SPICE is sensitive to cometary ions which have been picked up by the solar wind. Finally, CRAF carries dual 3-axis vector magnetometers, electron spectrometers for electron energies up to 30 keV, and sensors for measurements of hydromagnetic and plasma waves. The electric wave detector can also operate as a plasma sounder to study electron distributions with temperatures as low as 100 K. With this comprehensive array of plasma detectors, CRAF will address many of the questions left unanswered by the earlier comet flybys; a principal advantage is the ability to study the interaction of a comet with the solar wind over broad ranges of solar wind conditions and levels of cometary activity.

Asteroid Observations. En route to Kopff, CRAF will fly by two main belt asteroids: 88 Thisbe which has a diameter of 232 km, and 19 Fortuna which is 200 km in diameter. Both are primitive type asteroids with surface compositions believed to be similar to carbonaceous chondrite meteorites. CRAF will approach Thisbe from the sunlit side and Fortuna from the night side, at flyby speeds of 5.2 and 12.6 km/sec, respectively. The closest approach will be targeted for a distance of ~80 asteroid radii, which will allow each asteroid's mass and density to be determined to an accuracy of better than 10%, while still keeping the spacecraft beyond the range of any debris which might be trapped in orbit about the asteroid. All the remote sensing instruments described above will observe during the flybys. The spatial resolution at closest approach at Thisbe will be

112 meters/line-pair for the narrow angle camera, 4.6 km/pixel for VIMS, and 13.9 km/pixel for TIREX; resolution at Fortuna will be about 10% better. Observations with these instruments will allow determination of each asteroid's shape, surface topography, mean density, and rotation vector as well as the distribution of different material types on their surfaces. The gas and plasma detectors will search for any residual comet-like emissions from the asteroids, while CODEM will measure the properties of any fine debris in orbit around the asteroids. One of the key results will be comparison of the properties of the carbonaceous asteroids observed by CRAF with the stony asteroids observed by the Galileo spacecraft, addressing questions about the compositional heterogeneity and evolution of asteroids.

The Spacecraft. A computer-drawn picture of the CRAF spacecraft is shown in Figure 2. CRAF is 3-axis stabilized and will usually keep its 4-meter diameter high gain antenna pointed toward the Earth. Most of the experiments are mounted on one or the other of the articulated scan platforms shown in the Figure, or on the magnetometer boom. The same spacecraft will be used for the Cassini mission, with a different set of instruments mounted on the high-precision scan platform and with an instrumented turntable replacing the low-precision pointing platform. The Titan atmospheric entry probe will be mounted on the side of the spacecraft.

Options under study for future Mariner Mark II missions include a Neptune orbiter, a Pluto flyby, and a joint US-ESA mission to return a sample of a comet nucleus to Earth.

Current Status. Congressional action on the 1992 NASA budget provided less than full funding for CRAF/Cassini, leading to a slip to the 1997 launch to comet Kopff, from the previously planned 1996 mission to comet Tempel 2. Spacecraft and instrument development is continuing.

The work reported here was performed at the Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration.

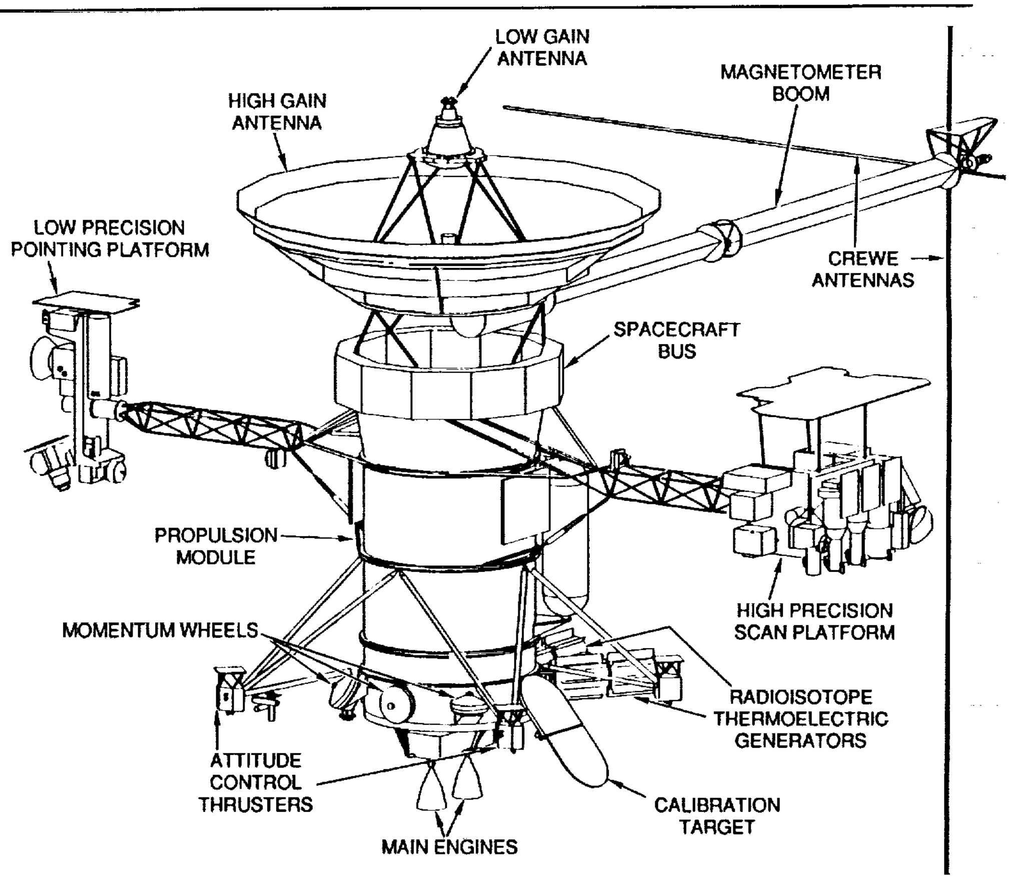

Figure 2. Computer-generated drawing of the Mariner Mark II spacecraft in CRAF configuration.